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Different Profiles of the Aerial Start Phase in Front Crawl

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[1]*CETAPS (EA 3832), Faculty of Sports Sciences, University of Rouen, Mont Saint Aignan, France;* [2]*Institute of Fundamental and Clinical Human Movement Sciences, Free University, Amsterdam, the Netherlands; and* [3]*Faculty of Sports, University of Porto, Porto, Portugal*

Abstract

Seifert, L, Vantorre, J, Lemaitre, F, Chollet, D, Toussaint, HM, and Vilas-Boas, JP. Different profiles of the aerial start phase in front crawl. *J Strength Cond Res* 24(2): 507–516, 2010—This study analyzed the kinematics and kinetics (jumping ability) of the aerial start phase in 11 elite front crawl sprinters. The aim was to determine whether a particular start technique leads to a short 15 m start time or whether several start profiles contribute equally well. All swimmers performed 3 starts using their preferential style, which was the grab start for all, followed by a 25-m swim at maximal velocity. Countermovement jump enabled to determine vertical jumping ability. Using a video device, phase durations, angles at takeoff and entry, and hip velocity were assessed. Correlation between all variables and the 15 m start time established the common features of an effective start but also revealed great intersubject variability. Cluster analysis enabled to distinguish 4 start profiles (flat, pike, flight, and Volkov), indicating that several individual profiles lead to short 15 m start times. It could be advised to consider the intersubject variability in relation to start time before favoring unique strategy.

Key Words biomechanics, swimming, cluster analysis, start profile

Introduction

A recent review indicated that the 15 m start time contributes up to 30% to the total race performance in the 50-m sprint (24), which underlines the importance of studying the start in swimming. Most of the biomechanical studies of the start compared swimmers' positions and evaluated the effect on time to reach the 15-m mark. The following review presents the different start positions and the conflicting results as regards the best solution to achieve a short 15 m start time.

In the oldest technique, the conventional or arm swing start, the swimmer can choose to grasp the block or not. Zatsiorsky et al. (37) noted 2 styles of conventional start (forward and full arm swing), whereas Lewis (23) observed 3 (arms back, straight arm backswing, and circular arm backswing). According to Bowers and Cavanagh (10) and Lewis (23), the conventional start enables longer flight distances than the grab start but at the expense of a longer block phase; the conventional start was therefore advised in the relay where the block time is not necessarily incorporated into the performance time.

Start techniques have changed over time, and swimmers can now put 1 foot (track start) or 2 feet (grab start) on the front edge of the block (19,26,30). Using the track start, swimmers can place the body weight toward the front edge (front-weighted track start) or the rear (slingshot track start) of the block (31,32). With the grab start, the hands grasp the front edge of the block either between the feet or at the outer edge of the feet (23).

Some start styles combine several techniques, as for example, the bunch start where swimmers place their feet as in a track start and their hands as in a conventional start (3). Another example is the tuck start where forward displacement of the center of gravity is used through compact body positioning, while the swimmer grasps the sides of the block (36). The aim of the tuck start is to decrease the time interval from starting stimulus to water entry (36). A version of the tuck start, called the handle start, was introduced to explore the effect of placing the center of gravity in a more forward position before the start (8,28). To do this, the Anti Wave Super Block was developed, with handles on the block that swimmers can grab behind the body (28).

Comparisons of these start techniques have shown conflicting results, and it is thus not possible to select a start position/style that will always result in faster start performance. In a comparison of 3 styles of conventional start and 2 styles of grab start, no significant difference in the 8 m start

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time was noted (23). Comparing the grab, track, and handle starts, Blanksby et al. (8) observed no significant improvement in the 10 m start time after a training intervention. Vilas-Boas et al. (31,32) compared the forward and rear projected positions of the center of mass in the track start and these 2 track start variants with the grab start. They found that the perceived differences in the block and aerial phases disappeared during the water gliding phase, ending in nonsignificant differences in start performance. Thus, according to Lyttle and Benjanuvatra (24), the superiority of a start style seems to be associated with the swimmer's preference rather than a real mechanical advantage.

Moreover, swim start performance also depends on the capacity to perform brief periods of very high-intensity, or anaerobic, exercise. One study reported that, after 8 weeks of strength training designed to improve vertical jumping ability, the improvement was not directly transferred to swim start performance (11). However, muscle volume was not determined in this study, even though anaerobic exercise performance is highly correlated with muscle mass (calculated from measurements of muscle volume) (4).

Although many studies have compared the different positions on the start block, a few have considered the aerial trajectory (takeoff and entry angles, body angles at takeoff and entry) in relation to the 15 m start time. The flat start and pike start (also called scoop, whip or hole start) have usually been described (25), but few studies have analyzed them, whereas these 2 styles of aerial trajectory would influence the underwater part and the 15 m start time. Counsilman et al. (13) showed a longer start time, greater takeoff and entry angles, and a shorter distance to head entry for the pike start than for the flat start. However, this study concerned young swimmers between 10 and 17 years and not elite sprinters. Conversely, for elite swimmers, Wilson and Marino (35) showed a shorter 10 m start time, greater entry angle, shorter distance to entry, and greater hip angle at entry for the pike start than for the flat start. Last, after 5 training sessions in which the swimmers had to combine a grab or track start and a pike or flat entry, Kirner et al. (18) reported that the grab start/flat entry showed a shorter 8 m start time and a smaller entry angle than the grab start/pike entry. This study did not compare specialists of each start style but required all participants to train and perform the 4 styles. Therefore, performance of the 8 m start time may have been influenced by the swimmers' preferential styles.

In view of the paucity of detailed studies on contemporary start styles, it could be suggested for coaches to examine the intersubject variability of the variables that describe the start aerial organization before concluding that there is only 1 strategy to start right. Therefore, the aim of this study was to analyze the aerial start phase in elite front crawl sprinters in terms of the kinematics and kinetics (vertical jumping ability). It was hypothesized that even if common features to the whole population are correlated to a short 15 m start time, the intersubject variability could be great, indicating that several individual profiles would result in similar 15 m start times.

Methods

Experimental Approach to the Problem

A great many studies have analyzed the start position (conventional vs. grab vs. track), but a few have analyzed the different styles possible for a given start position. For this reason, the aerial phase of the start should be revisited. Indeed, the conflicting results for start positions and styles of aerial trajectory have made it difficult to establish a relationship between a start style and start time performance. Before concluding to right or mistake in the start organization, it would be interesting for coaches to determine whether specific start styles are linked to short 15 m start times or whether several start profiles can result in the same short start time. A descriptive analysis would enable to examine (a) the common features that are correlated to a short 15 m start times and (b) the intersubject variability (from the standard deviation of each variable) to determine several effective profiles. Recent overviews about intersubject variability have shown that cluster analysis was an appropriate method to distinguish profiles of subject (5,12). Previous studies have already used cluster analysis to classify the foot's impulse symmetry in the grab and track start styles (7) and to classify the backstroke start regarding swimmers' body segment vectors (34).

Subjects

Eleven, elite, male sprint specialists in front crawl voluntarily participated in this study (23.4 $\pm$ 3.6 years; 189.2 $\pm$ 6.6 cm; 80 $\pm$ 9.3 kg; mean time for a 100-m front crawl in a 50-m pool: 50.7 $\pm$ 1.1 seconds). The protocol was fully explained to the subjects, who were informed of the experimental risks and signed an informed consent document before the investigation. Moreover, the study was approved by an institutional ethics committee, composed by an official review board. This group was exclusively composed of elite swimmers, for which skill level was expressed as a percentage of the world record for a 100-m front crawl: the mean was 94.5 $\pm$ 1.9%. At the moment of the experimentation, the swimmers trained 21.0 $\pm$ 1.2 hours per week and had 12.6 $\pm$ 2.3 years of practice. The group included 2 Junior European Champions, a finalist of 4 Olympic Games, and 2 bronze medalists at the World Championships.

Procedures

Swim Trial. Each swimmer executed a dive start and then swam a 25-m front crawl at his maximal velocity. Three trials using the preferential start position were required, and for the entire population, this was the grab start.

Video Analysis. Three lateral aerial video cameras (50 Hz, Panasonic NV-MS1 HQ S-VHS; Panasonic, Paris, France)

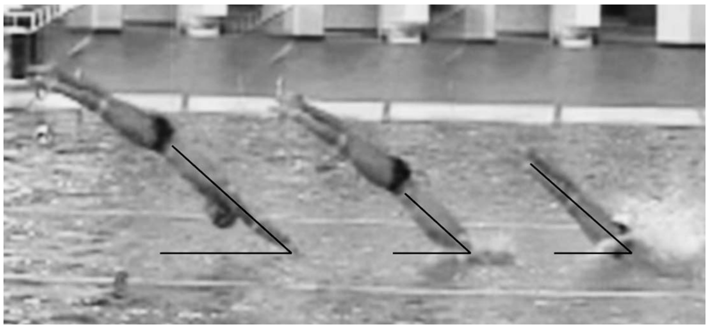

Figure 1. Entry angle: at the hand entry (angle between the horizontal axis, the wrist, and the hip), at the shoulder entry (angle between the horizontal axis, the shoulder, and the hip), at the hip entry (angle between the horizontal axis, the hip, and the ankle).

with rapid shutter speed (1/1000 seconds) were connected to an audiovisual mixer, a video timer, a video recorder, and a monitoring screen to genlock and mix the 3 lateral views on the same screen. The first camera was placed at the edge of the pool and videotaped the block phase, enabling measurement of the body angles at takeoff and the total takeoff angle. The second camera was placed 5 m from the edge of the pool and videotaped the flight phase, the body angles at hand entry, and the total entry angle. The third camera was placed in front of the 15-m mark, which was attached on the water line 15 m from the start of the pool, and videotaped the swimmer from the moment when the head broke the surface of the water to the end of the 15 m.

The videotapes of the first and second cameras were digitized with DartFish software (Dartfish ProSuite4.0, 2005; Switzerland) at a frequency of 50 Hz. Four body marks (ankle, hip, shoulder, and wrist on the right side) were digitized at takeoff and hand entry, and the hip mark was then digitized with DartFish 3 frames before and 3 frames after the hand entry, as previously done in gymnastics (6). The reliability of the digitization was assessed by digitizing the 4 body marks 4 times for 4 trials of 3 swimmers; the average error of digitization was 3.42%.

TABLE 1. Mean, *SD*, and minimum and maximum data for the kinematic and kinetic variables for the whole population.*

Variables	Mean	*SD*	Minimum	Maximum
15 m start time (s)	6.43	0.38	5.14	7.07
Block phase (s)	0.84	0.06	0.73	0.98
Flight phase (s)	0.31	0.06	0.20	0.44
Entry phase (s)	0.29	0.07	0.18	0.44
Block phase (%)	13.1	0.9	11.5	15.6
Flight phase (%)	4.9	1.1	3.4	7.3
Entry phase (%)	4.6	1.0	2.9	6.2
Distance to hand entry (m)	3.8	0.3	3.0	4.4
Hip velocity at hand entry ($m \cdot s^{-1}$)	5.70	0.70	4.25	6.77
Angle at takeoff				
Ankle/hip/shoulder (°)	152.4	7.7	137.3	168.6
Hip/shoulder/wrist (°)	121.4	39.9	0.6	165.3
Horizontal axis/ankle/hip (°)	24.0	5.5	11.5	33.5
Angle at hand entry				
Horizontal axis/wrist/hip (°)	37.1	3.8	29.1	43.5
Hip/shoulder/wrist (°)	174.9	5.4	162.5	182.0
Ankle/hip/shoulder (°)	161.7	10.1	138.0	179.8
Angle at shoulder entry				
Horizontal axis/shoulder/hip (°)	36.9	5.8	24.8	51.2
Angle at hip entry				
Horizontal axis/hip/ankle (°)	38.6	4.7	31.4	48.8
CMJ: height (cm)	45.0	8.0	36.0	61.0
CMJ: power ($W \cdot kg^{-1}$)	14.5	1.4	12.9	17.2
CMJ: power ($W \cdot L^{-1}$)	114.7	11.7	91.8	130.1

*CMJ = countermovement jump; $W \cdot L^{-1}$ = power expressed relative to lean leg volume.

TABLE 2. Results of Pearson's correlation tests (r = coefficient of correlation; p = significant p value).*

	Angle at takeoff: hip/shoulder/wrist (°)	Angle at takeoff: horizontal axis/ankle/hip (°)	Distance to hand entry (m)	Angle at hand entry: horizontal axis/wrist/hip (°)	Block phase (%)	Flight phase (%)	Hip velocity at hand entry ($m \cdot s^{-1}$)
Angle at takeoff Horizontal axis/ankle/hip (°)	$r = -0.51$ $p = 0.002$						
Angle at hand entry Horizontal axis/wrist/hip (°)		$r = 0.57$ $p = 0.001$					$r = 0.49$ $p = 0.041$
Angle at hand entry Hip/shoulder/wrist (°)				$r = 0.4$ $p = 0.023$			
Angle at hand entry Ankle/hip/shoulder (°)		$r = -0.46$ $p = 0.008$		$r = -0.61$ $p = 0.0001$			
Block phase (%)	$r = 0.4$ $p = 0.021$		$r = 0.38$ $p = 0.029$				
Flight phase (%)		$r = 0.61$ $p = 0.0001$	$r = 0.54$ $p = 0.001$	$r = 0.45$ $p = 0.009$	$r = 0.36$ $p = 0.037$		
CMJ: height (cm)		$r = 0.39$ $p = 0.031$				$r = 0.44$ $p = 0.014$	
CMJ: power ($W \cdot kg^{-1}$)		$r = 0.4$ $p = 0.028$				$r = 0.44$ $p = 0.014$	
CMJ: power ($W \cdot L^{-1}$)	$r = -0.44$ $p = 0.014$	$r = 0.58$ $p = 0.001$					
15 m start time (s)		$r = -0.43$ $p = 0.012$	$r = -0.36$ $p = 0.043$	$r = -0.47$ $p = 0.006$	$r = -0.51$ $p = 0.003$	$r = -0.69$ $p = 0.0001$	

*CMJ = countermovement jump.

Figure 2. Start of Dimitri Volkov at the Canet Meeting in June 1988, showing a close upper limb/trunk angle.

Kinematic Variables.

- The *15 m start time* was the time between the starting signal and the moment when the swimmer's head reached the 15-m mark.
- The *block* phase was the time between the starting signal and the moment when the swimmer's feet left the block.
- The *flight* phase was the time between leaving the block and the hand's first contact with the water.
- The *entry* phase was the time between the hand's first contact with the water and the foot entry.

The duration of each phase was measured for each dive with a precision of 0.02 seconds. The absolute duration of each phase is expressed in seconds, whereas the relative duration is expressed in percentage of the 15 m start time.

- The *distance to entry* was the horizontal distance measured between the block or starting wall and the hand entry, expressed in meters.
- The *hip velocity* at hand entry into the water was calculated from the hip position 3 frames before and 3 frames after the hand entry. Therefore, 6 instantaneous values of hip velocity were obtained within 2 frames and then averaged. These calculations were made for the horizontal and vertical directions and were averaged to obtain the resultant velocity.
- Two *body angles* (lower limbs/trunk angle: angle between the ankle, hip, and shoulder; upper limbs/trunk angle: angle between the hip, shoulder, and wrist) were analyzed *at the takeoff and at hand entry.*
- The *takeoff angle*: the angle between the horizontal axis, the ankle, and the hip.
- The *entry angle*: the angle between the horizontal axis and the body. This angle was quantified at 3 points (Figure 1): hand entry (angle between the horizontal axis, the wrist, and the hip), shoulder entry (angle between the horizontal axis, the shoulder, and the hip), and hip entry (angle between the horizontal axis, the hip, and the ankle).

These variables were used to distinguish 2 main start styles: the pike and the flat start. In the literature (24,25), the pike start was defined by (a) a great aerial trajectory, both spatially (great takeoff and entry angles) and temporally (long relative duration of block and flight phases) and (b) flexed lower limbs (i.e., small lower limbs/trunk angle) at the takeoff and hand entry. Conversely, the flat start was defined by (a) a short relative duration of the flight phase and (b) extended limbs.

Kinetic and Anthropometric Variables. Thirty minutes before the swim trials and after a warm-up, subjects were asked to jump vertically as high as possible; this countermovement jump started from an erect standing position, and the arms were allowed to swing. Each swimmer made 2 countermovement jumps (CMJs) separated by 5 minutes of recovery. For each trial, the vertical jump height (cm) and the power ($W \cdot kg^{-1}$ and $W \cdot L^{-1}$) were recorded and calculated by Optojump (Microgate, Bolzano, Italy) (22).

Left lean leg volumes were calculated from 7 measurements: leg circumference above, at, and below the knee and subcutaneous skinfold measurements taken at 4 sites on the thigh and calf; these data were used to estimate leg and muscle volumes (17). Results from Rice et al. (29) showed that volume measured by anthropometric techniques closely approximates computed tomography scan data.

Statistical Analyses

Pearson's correlation analysis determined the relationships among the variables ($n = 3$ trials $\times$ 11 swimmers = 33) for the whole population to establish the common features that are correlated with a short 15 m start time. Intersubject variability was examined by a cluster analysis, using Ward's method with a squared Euclidean distance, applied to all the variables to classify the participants. The results of the cluster analysis yielded a dendrogram; Kruskal-Wallis tests then analyzed the variables that significantly differentiated the clusters.

Before considering the 3 trials of each swimmer, the intrasubject variability was examined by checking that all the 3 trials of each swimmer were grouped in the same cluster.

All tests were performed with Minitab 14.10 (Minitab, Inc., 2003, Paris, France), and the level of significance was set at $\alpha = 0.05$.

Table 3. Mean, *SD*, and significant differences of kinematic variables between the 4 clusters.

	Flat start		Pike start		Flight start		Volkov start	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
15 m start time (s)	6.58	0.32	6.33	0.46	6.07	0.19	6.47	0.11
Block phase (s)	0.86	0.05	0.86	0.06	0.81	0.03	0.76†‡	0.01
Flight phase (s)	0.27	0.04	0.34	0.06	0.39†	0.04	0.32*	0.01
Entry phase (s)	0.31	0.06	0.29	0.09	0.27	0.01	0.27	0.03
Block phase (%)	13.1	0.9	13.5	1.1	13.3	0.1	11.7*†‡	0.2
Flight phase (%)	4.2	0.5	5.5	1	6.5†	0.7	4.9*	0.1
Entry phase (%)	4.7	0.8	4.5	1.3	4.5	0.3	4.1	0.8
Distance to hand entry (m)	3.8	0.2	3.8	0.5	4	0.3	3.6	0.3
Hip velocity at hand entry ($m \cdot s^{-1}$)	5.59	0.75	6.48*	0.51	5.40*	0.14	5.64‡	0.49
Angle at takeoff								
Ankle/hip/shoulder (°)	150.9	9.3	154	6.2	153.1	2.4	155.4	4.2
Hip/shoulder/wrist (°)	145.7	10	132.9	12.7	81.8*†	10.5	22.3*†‡	19.2
Horizontal axis/ankle/hip (°)	19	3.3	26.8*	3.6	29.4†	3.6	27.8†	2.4
Angle at hand entry								
Horizontal axis/wrist/hip (°)	34.3	3.9	39.7*	2.8	36.7	2.2	37	3.1
Hip/shoulder/wrist (°)	171.3	9.9	176	5.3	170.8	4	173.3	6.7
Ankle/hip/shoulder (°)	167.2	6.5	152.6*	6.6	168.8*	8.9	166.4‡	8.8
Angle at shoulder entry								
Horizontal axis/shoulder/hip (°)	33.7	4.2	40*	6.8	38.3	5.2	38.5	1.8
Angle at hip entry								
Horizontal axis/hip/ankle (°)	36.7	3.9	41.2	5.4	37.9	2.8	37.7	4.4

*Significantly different with the previous cluster.
†Significantly different with the flat start cluster.
‡Significantly different with the pike start cluster.

Results

The mean takeoff angle was 24°, with a range from 137.3 to 168.6°, with the swimmers' lower limbs and trunks nearly extended (mean ankle/hip/shoulder angle was 152.4°) (Table 1). Conversely, the upper limbs/trunk angle at takeoff varied markedly (from 0.6 to 165.3°), suggesting that many strategies were employed to use the hip extension capacity in the push-off. The correlation tests (Table 2) showed that the swimmers who started with a takeoff angle closer to the horizontal axis (near 10 vs. 30°) had greater upper limbs/trunk angles (near 160 vs. 0°), suggesting that a flat aerial trajectory was associated with an extended body position to ensure streamlined body posture upon water entry. The correlation tests (Table 2) also indicated that the smaller the upper limbs/trunk angle, the shorter the relative duration of the block phase was, suggesting that having the arms along the trunk led to stretching forward and upward by an impulse of the shoulders (called "Volkov" style in the "Discussion").

The mean entry angle was 37.1°, but this varied from 29.1 to 43.5° (Table 1). Table 1 also shows that the swimmers had the upper limbs (mean upper limbs/trunk angle was 174.9°), the lower limbs (mean lower limbs/trunk angle was 161.7°), and the trunk almost extended at hand entry. However, the lower limbs/trunk angle varied from 138.1 to 179.8°. Thus, the correlation tests (Table 2) enabled us to distinguish 2 start styles: the pike and the flat start. Indeed, these tests (Table 2) showed that a long relative block phase was associated with a great distance to hand entry. The long time spent on the block was associated with a long relative flight phase, which

Table 4. Mean, *SD*, and significant differences of the kinetic variables between the 4 clusters.*

	CMJ					
	Height (cm)		Power ($W \cdot kg^{-1}$)		Power ($W \cdot L^{-1}$)	
Clusters	Mean	*SD*	Mean	*SD*	Mean	*SD*
Flat start	46	7	14.6	1.2	116.4	8.8
Pike start	40	6	13.7	0.9	110.2	13.7
Flight start	61†§	0	17.2†§	0	130.1†§	0
Volkov start	43†	0	14.3†	0	110.6†	0

*CMJ = countermovement jump.
†Significantly different with the previous cluster.
§Significantly different with the flat start cluster.

TABLE 5. Comparison of angle, distance to entry, and phase duration between several studies that analyzed start.*

Studies	Skill level	Takeoff angle (°)	Distance to hand entry (m)	Entry angle (°)	Block duration (s)	Flight duration (s)
Our study	Elite level	24 ± 5.5	3.79 ± 0.34	37.1 ± 3.8	0.84 ± 0.06	0.31 ± 0.06
Miller et al. (26)	Division 3 NCAA	6.23 ± 1.55	3.31 ± 0.12	39.54 ± 2.64	0.95 ± 0.04	0.25 ± 0.04
Kruger et al. (19)	National level	31.5			0.91 ± 0.14	0.33 ± 0.05
Takeda and Nomura (30)	Elite college competitive	Takeoff angle −1.6 ± 4.1 Body angle at takeoff 24.7 ± 3.7	3.25 ± 0.2			
Counsilman et al. (13)	National college	Pike 17.64 ± 11.65 Flat 5.08 ± 8.51	2.9 ± 0.3 3 ± 0.3	47.36 ± 7.66 31.02 ± 7.5		
Houel et al. (16)	National level	−1.55 ± 5.9				
Lyttle and Benjanuvatra (24)	Review	−5 to 10		Pike 50 Flat 30–40		
Heusner (15)	Theoretical model	13				
Blitvich et al. (9)			4.93 ± 0.56	42 ± 7		
Wilson and Marino (35)	Olympic team	Pike 25.44 ± 3.13 Flat 19.85 ± 4.30	3.66 ± 0.41 3.93 ± 0.44	39.38 ± 3.27 21.25 ± 5.59		
Kirner et al. (18)	Competitive level NCAA			Pike 44.69 Flat 35.73		
Maglischo (25)		30–40	3–4			0.3–0.4

*NCAA = National Collegiate Athletic Association.

should result in a great distance covered at hand entry. Indeed, the relative duration of the flight phase was positively correlated with the takeoff angle and the entry angle (angles between the body and the horizontal axis). The takeoff angle was positively correlated with the entry angle, indicating that higher values of these 2 angles led to a pike entry, whereas low values for the takeoff and entry angles led to a flat entry. A great entry angle was associated with high hip velocity at hand entry (Table 2). Then, great takeoff and entry angles were associated with small lower limbs/trunk angles, suggesting that an aerial trajectory (pike start) was related to flexed lower limbs.

Last, regarding the kinetic variables, the flight phase duration and the takeoff angle were associated with the height and power developed by the swimmer during the CMJ, indicating that a great impulse would lead to a pike start (Table 2).

The 15 m start time was negatively correlated with the takeoff and entry angles, the distance to hand entry, and the durations of the block and flight phases (Table 2). These results indicate that a short 15 m start time was associated with a pike start; however, large standard deviations were noted for several variables when the whole population was considered. This observation suggested the use of cluster analysis for further data processing.

The cluster analysis enabled us to classify the swimmers into 4 groups: the "flat" start group (5 swimmers), the "pike" start group (4 swimmers), the "flight" start group (1 swimmer), and the "Volkov" start group (1 swimmer) (Figure 2). The dendrogram showed that the 3 trials of each swimmer belonged to the same cluster, confirming that high skill levels correspond to low intrasubject variability. Regarding the results of the Kruskal-Wallis tests, 10 kinematic variables (Table 3) and 3 kinetic variables (Table 4) significantly differentiated the 4 clusters. The 15 m start time did not significantly differ between the 4 clusters, thus demonstrating that several start styles are used by elite male front crawl sprinters.

Discussion

Our results for the takeoff and entry angles, the distance to hand entry, and the phase durations were in the ranges reported in the literature. However, the large standard deviation in our data and the differences in the results noted in the literature may be due to differences in the methods of analysis and the skill levels, styles, and leg power of the swimmers.

Moreover, our results indicated that the 15 m start time was not correlated with a start style, suggesting that several start styles could lead to similar 15 m start times. This assumption is theoretically acceptable because a short 15 m start time depends on the capacity to generate great takeoff velocity, which arises from the compromise between a long time spent on the block to create more force and a short time on the block to minimize the time deficit (24). In other words, the swimmers' aerial trajectories resulted from a compromise between the pike and flat styles. The pike style leads to a longer flight time, with a greater distance covered and far lower resistance than upon entering the water. Conversely, with a flat style, swimmers have a short time for leaving the block, which is a gain of time, but it leads to quick water entry with low hip velocity and high water resistance. Our study did not focus on the underwater phase of the start; therefore, no conclusion can be drawn regarding the importance of high hip velocity at hand entry. For example, although high vertical hip velocity is associated with the pike style, the transition to horizontal velocity could lead pike-style starters to lose the high velocity achieved in the aerial phase. However, our results indicated that the entry angle (body position/horizontal axis) remained stable at the 3 points assessed (e.g., at the hand, shoulder, hip entry; Figure 1), suggesting that all the swimmers maintained stable body position through the entry phase (i.e., in streamlined position as regards the water surface), which would result in a small entry hole, whatever the start style.

On one hand, the cluster analysis showed low intrasubject variability. Indeed, the 3 trials of each swimmer are included in the same cluster, confirming that high skill levels corresponded to low intrasubject variability (as previously observed in javelin throwing (5)).

On the other, the cluster analysis revealed great intersubject variability that enables to distinguish 4 profiles of the aerial phase of grab start. In the *flat* start cluster, the upper limbs were almost extended at takeoff (146°), indicating that the swimmers used their upper limbs to push off in association with a long block phase (0.86 seconds and 13.1%). In agreement with previous studies (13,18,25,35), the flat start cluster showed the smallest takeoff (19°) and entry (34.3°) angles. This flat trajectory had the shortest flight phase (0.27 seconds and 4.2%) and an extended lower limb/trunk angle (167.1°), ensuring a streamlined entry with lower hip velocity at hand entry (5.59 $m \cdot s^{-1}$) than the pike style.

The *pike* start cluster, like the flat start cluster, showed a greater upper limb/trunk angle (132.9°) at takeoff and a longer block phase (0.86 seconds and 13.5%) than the *flight* and *Volkov* clusters. The greater upper limb/trunk angle indicated that these swimmers favored a great arm swing to achieve a longer flight phase (0.34 seconds and 5.5%) than observed in the flat start cluster. According to Harman et al. (14) and Lees et al. (21), the arm swing helps to increase the height (28%) and velocity (72%) of the center of mass at takeoff in the vertical jump. The arm swing also leads to a longer jump (in the long jump) by increasing the distance (21.2%) and the velocity (12.7–15%) of the center of mass at takeoff (1,2). In line with previous studies (13,18,24,35), which defined the pike style by an entry angle of about 40–45°, the pike start in our study was characterized by a great takeoff angle (26.8°) and a significantly greater entry angle and smaller lower limb/trunk angle (152.6°) than the other styles. Wilson and Marino (35) noted that combining a great entry angle and great hip flexion facilitates a pike style with small hole size. Assessing the entry angle at 3 points enabled us to estimate the hole size and glide depth. The pike style showed the greatest entry angle at these 3 points (hand entry 39.7°, shoulder entry 40.0°, and hip entry 41.2°) in association with the highest hip velocity at the hand entry (6.48 $m \cdot s^{-1}$), suggesting small hole size. Lyttle and Benjanuvatra (24) also reported the highest velocities of the pike style (between 4 and 6 $m \cdot s^{-1}$) at the entry and glide phases. Whether or not high hip velocity at entry was a benefit, the finding of the greatest entry angle in our pike style cluster may indicate greater depth than in the flat style (33), high deceleration during the entry and glide phases, and high drag due to the need to turn the body into a horizontal movement direction.

The third cluster corresponded to a *flight* start. Only 1 swimmer was in this cluster, a start specialist. The characteristics were as follows:

- A perpendicular upper limb/trunk angle (81.8°) at takeoff that would explain the short block phase (0.81 seconds and 13.3%).
- The longest flight phase (0.39 seconds and 6.5%) that was significantly correlated ($r = 0.44$) with the greatest height and power attained in the CMJ (respectively, 61 cm, 17.2 $W \cdot kg^{-1}$, 130.1 $W \cdot L^{-1}$). Although CMJ performance is not directly transferred to the dive start (11,20), our results agree with those of Zatsiorsky et al. (37), who showed a correlation between flight time and the swimmer's jumping ability ($r = 0.68$). Similarly, Counsilman et al. (13), Miyashita et al. (27), and Pearson et al. (28) noted a significant correlation between swim start performance and vertical jumping or leg extensor power. The long flight phase of this swimmer could also have been due to the great takeoff angle (29.4°), with both of these characteristics contributing to the great distance to entry (4 m). Finally, as recommended by Lyttle and Benjanuvatra (24), this swimmer spent enough time applying great force on the block but not too much and thus managed to have a relatively short block phase duration.
- His entry angle (36.7°) was a compromise between the flat and pike start clusters. Indeed, the longer flight time did not result in the great entry angle observed in the pike style but led to the lowest hip velocity at hand entry (5.40 $m \cdot s^{-1}$).

The fourth cluster corresponded to a *Volkov* start, named for the first swimmer to use it, Dimitri Volkov, the Russian bronze medalist of the 100-m breaststroke at the Olympic Games of Seoul in 1988 (Figure 2). Only 1 swimmer belonged to this cluster, the participant in 4 Olympic Games. The Volkov style was characterized by the smallest upper limb/trunk angle at takeoff (22°), indicating that the swimmer stretched the shoulders upward and forward, in correlation ($r = 0.4$) with the shortest block phase (0.76 seconds and 11.7%) and a short flight phase (0.32 seconds and 4.9%).

Practical Applications

The analysis of the aerial phase of the swim start using the grab technique showed that several profiles led to similar 15 m start times. Four profiles were distinguished: (a) In the first profile, swimmers favored a long flight time that enabled them to delay the time when the body would have aquatic resistance to overcome, resulting in a "pike" aerial trajectory; (b) A second profile was characterized by a short block phase that gained time but led the body to quickly overcome aquatic resistance, resulting in a "flat" aerial trajectory; (c) The swimmer with the third profile optimized this double constraint (short block phase and long flight phase) at takeoff by his capacity to apply great force with his leg extensors in relation to an arm swing, resulting in a "flight" style; and (d) The swimmer showing the last profile used a "Volkov" style, that is, the impulse was provided by the shoulder instead of an arm swing at takeoff. No one start style led to a better 15 m start time, so coaches need to detect the preferential style of each swimmer with regard to his or her jumping ability, capacity to have a small hole size (whatever the form of the aerial trajectory), and capacity to minimize the velocity decrease during the entry and glide phases.

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